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Title: ATMOSPHERIC DISPERSION MODELING FOR
RADIOLOGICAL ACCIDENT ANALYSES AT LANL
NUCLEAR FACILITIES

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Submitted to:

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Atmospheric Dispersion Modeling
for
Radiological Accident Analyses
at
LANL Nuclear Facilities

February 20, 2002

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I. Background

I.A. SAR requirements for off-site consequence analysis

Part of a facility safety analysis frequently includes an estimate of accident consequences to people outside and downwind of the facility from a release of radioactive material. Depending on the results of this estimation, controls may be identified. These controls may be designated as technical safety requirements depending on the severity of the consequences and the likelihood of the accident occurring.

Estimates of consequences to people located off-site are examined as a specific case. If the estimated dose to the maximally exposed off-site individual (MOI) exceeds the evaluation guideline of 25 rem, the controls identified to prevent or mitigate the accident are called "Safety Class" and are subject to a very high level of quality assurance and quality control.

There are in use several computer codes that provide atmospheric dispersion estimates for the purpose of estimating downwind doses from radionuclide releases. These codes include a significant number of parametric inputs provided by the user of the code. The results obtained can depend strongly on these parameter values and how the codes are run. This paper is an attempt to standardize this analysis process at Los Alamos National Laboratory (LANL).

Included as appendices are atmospheric dispersion values (χ/Q 's) for ground-level and several elevated releases from each of the nuclear facilities at LANL using the guidance provided by this document. Buoyant, or wake effect releases or releases with other characteristics than those described in this report are the responsibility of the analyst. All departures from the guidance provided in this report must be technically justified by the analyst.

Once the χ/Q is known, inhalation dose is estimated by:

$$Dose(rem) = ST * SpA * DCF * \chi / Q * BR \quad (1)$$

where: ST = source term (grams)

SpA = specific activity of radionuclide (Ci/gram)

DCF = dose conversion factor (rem/Ci inhaled)

χ/Q = atmospheric dispersion factor (sec/m³)

BR = breathing rate (3.3×10^{-4} m³/s, from ICRP 23)

I.B. Acknowledgements

Credit is due to Jackie East, Westinghouse Safety Management Solutions, Savannah River Site and Julie Gregory, Sandia National Laboratories who were of great help with the MACCS2 code and for review of this paper.

II. DOE-STD-3009-94, Appendix A

In January, 2000, the DOE issued Change Notice No. 1 to DOE-STD-3009-94 (Ref. 6). The change was the addition of Appendix A, "Evaluation Guideline". Pages A-6 to A-7 include a description of atmospheric dispersion and how it should be determined. The first paragraph in this section is as follows:

"The 95th percentile of the distribution of doses to the MOI (*maximumally exposed off-site individual*), accounting for variations in distance to the site boundary as a function of direction, is the comparison point for assessment against the EG (*evaluation guideline*). The method used should be consistent with the statistical treatment of calculated χ/Q values described in regulatory position 3 of NRC Regulatory Guide 1.145 for the evaluation of consequences along the exclusion area boundary. The determination of distance to the site boundary should be made in accordance with the procedure outlined in position 1.2 of Regulatory Guide 1.145."

A discussion of the determination of distance to the site boundary is included in Section IV.B below.

III. NRC Regulatory Guide 1.145

The pertinent part of position 3 is:

"Using the χ/Q values calculated according to regulatory position 1, an overall cumulative probability distribution for all directions combined should be constructed. A plot of χ/Q versus probability of being exceeded should be made, and an upper bound curve should be drawn. The 2-hour χ/Q value that is exceeded 5 percent of the time should be selected from this curve as representing the dispersion condition indicative of the type of release being considered."

It should be emphasized that the dose estimates derived by this method are statistical doses in that they can be thought of as expectation values derived by weighting the directions and associated distances by the frequency with which the wind blows in each direction. As such they should not be presented as real dose estimates to any given off-site individual located at a single direction and distance.

Also, calculations of this kind are highly uncertain. There are many papers in the literature discussing uncertainties in atmospheric dispersion models (see for example Ref. 7). For the most part, these uncertainties are due to the random nature of atmospheric phenomena and oversimplifications of the models such as the handling of meteorological data. Attempts to predict a dose at a specific location are uncertain by as much as an order of magnitude. Statistical approaches as described in Regulatory Guide 1.145, position 3, are less uncertain, but are probably not any better than a factor of 2.

IV Gaussian Dispersion Model

Regulatory position 1 uses a gaussian dispersion model for stack (or point source) releases (Section 1.3.2) and a customized version of a gaussian dispersion for building wake releases (Section 1.3.1).

A complete technical discussion of the gaussian dispersion model can be found in a number of references. One of the most commonly used is by Turner (Ref. 3).

IV.A. MACCS2

There are a number of computer codes that provide gaussian atmospheric dispersion calculations. The MELCOR Accident Consequence Code System (MACCS) is the most commonly used code at DOE facilities. The latest version is version 2, hence the name MACCS2.

This code was written for the NRC for the evaluation of nuclear reactor accidents. It doesn't directly derive χ/Q values according to regulatory position 3 of Regulatory Guide 1.145 because it doesn't derive a single value of χ/Q for "all directions combined", but this single value can be constructed from the MACCS2 output with the use of a post-processor as described below.

Wake effects are not calculated by MACCS2 in a manner consistent with regulatory position 1 of Regulatory Guide 1.145; there is no computer code that does to this author's knowledge. The wake effects feature of MACCS2 is described below but the analyst should compare its results with those of regulatory position 1. For the most part, off-site locations at LANL are sufficiently distant so that building wake results are not significantly different from point source results.

Means for determining the distance to the site boundary as a function of direction is provided by Regulatory Guide 1.145, Section 1.2. It is left to the analyst to consult this reference. A file containing this information is required by the post-processor. It will be facility-specific. This is not intended as instruction on how to run the MACCS2 code but the various input parameters to a gaussian dispersion model are described in terms of the MACCS2 code parameters.

IV.A.1. ATMOS

ATMOS is the name of the MACCS2 subroutine that calculates χ/Q values from the various input parameters provided by the user. The following sections describe those parameters and their expected values for consequence analysis at Los Alamos.

IV.A.1.a. Spatial Endpoint Distances

MACCS2 divides the two-dimensional universe surrounding the release point into polar coordinates. Distance from the source is binned into radial distances defined by the user. While any set of distances can be defined, so long as they are at least of 100 meter increments, the user must be careful that the grid is defined with sufficient resolution to provide a meaningful calculational output. Also, the mid-point of the last spatial interval must be greater than or equal to the maximum direction-dependent site-boundary distance as defined in the data file, *.bnd, used with the post-processor, POSTMAX (see IV.B. below).

A suggested set of spatial endpoint distances (in km) for TA-55 is:

GESPAEND001	.05	.15	.25	.35	.45	
GESPAEND002	.55	.65	.75	.85	.95	
GESPAEND003	1.05	1.55	2.05	2.55	3.05	
GESPAEND004	3.55	4.05	4.55	5.05	5.55	6.05

IV.A.1.b. Wet Deposition

Wet deposition is a plume depletion mechanism due to wash-out from precipitation.

The model used by MACCS2 depletes the source term by a fraction given by:

$$\exp(-c_{wash1} * \text{rain duration} * \text{rain intensity}^{c_{wash2}}) \quad (2)$$

In support of risk assessments of nuclear reactors, the NRC sponsored work by Sandia National Laboratories to recommend parametric values for MACCS dispersion analyses (NUREG/CR-4551) (Ref. 2). The range suggested for the variable c_{wash1} is 3.0×10^{-5} to 3.0×10^{-4} and the range suggested for the variable c_{wash2} is 0.7 to 0.9 with the recommended single values of 9.5×10^{-5} and 0.8 (mid-range values).

Real LANL meteorological data in combination with parameter values at the upper end of the recommended range reduces the estimated doses by only 1%. The heavier precipitations experienced at LANL for a one-hour period reduce the dose estimate for that hour by an order of magnitude or more, but these heavy rains occur with insufficient

frequency to affect significantly the dose estimates when data for an entire year are taken into consideration.

It is expected, therefore, that wet deposition will not be considered in consequence analyses at LANL.

IV.A.1.c. Dry Deposition

Dry deposition is a plume depletion mechanism due to gravitational settling and surface interaction effects. The literature distinguishes between gravitational settling and surface interactions as different phenomena, reserving the term "dry deposition" for the surface interaction mechanism. MACCS2, however, takes both into account with a single number with units of speed (m/s), and calls it "dry deposition".

The NRC study referenced above (Ref. 2) recommends a range of values for dry deposition velocity of 0.03 to 3.0 cm/s with a single best value of 0.3 cm/s. S. Acharya of NRC (and now DOE) recommended a value of 1.0 cm/s). Since these values were derived for nuclear reactor accidents releasing fission products, they may or may not apply to non-reactor nuclear facilities depending on the specific accident scenarios.

Use of dry deposition velocity in the MACCS2 code makes almost no difference in down-wind dose estimates at the low end of this range and a significant difference at the recommended value or the upper end of the range. Table I shows the results of MACCS2 dose estimates at a distance of 1.0 km from a ground-level Pu-239 release with 95% meteorology using different dry deposition velocities over the suggested range. The differences are due to plume depletion and its effect on the inhalation pathway. If the radionuclide is a strong gamma emitter (e.g. Co-60), the resulting ground shine can also be significant if exposures are followed for long times after the passage of the plume. This, however, is not typically done in accident analyses because it is assumed that re-location of the receptors (worker or public) can be accomplished in the time frame of hours if necessary.

TABLE 1

Vd (cm/s)	Dose (rem/Ci-released)	Ratio Dose(Vd)/Dose(Vd=0)
0	1.93×10^{-1}	1.0
3×10^{-2}	1.89×10^{-1}	0.98
3×10^{-1} (recommended by NUREG)	1.58×10^{-1}	0.82
1×10^0 (recommended by Acharya)	1.09×10^{-1}	0.56
3×10^0	5.18×10^{-2}	0.27

Dry deposition velocity depends on particle size, density, wind speed, and surface roughness. Even with dense particles in the respirable range, the dry deposition velocity is more appropriately represented by the low end of the range referenced above because the 95% meteorology used for estimating off-site dose, is a low-dispersing environment. Therefore, unless a technically defensible argument can be made for some specific deposition velocity, it is expected that dry deposition will not be included in consequence analyses at LANL.

IV.A.1.d. Dispersion Parameters (σ_y and σ_z)

The choice of dispersion parameters strongly affects the dose estimates. The dose estimate is proportional to the estimated dispersion (χ/Q) which, for a ground-level receptor at the plume centerline is:

$$\chi / Q = \frac{1}{\pi u \sigma_y \sigma_z} \exp \left[-\frac{H^2}{2\sigma_z^2} \right] \quad (3)$$

where: u = wind speed, and
 H = release height

There are quite a few systems of dispersion parameter values reported in the literature and any system can be used in a MACCS calculation provided it can be represented either as a power function of distance for each of six stability classes or as a complete table. The power function representations included in the MACCS2 User's Guide are:

- Tadmor and Gur representation of the Pasquill-Gifford values,
- Karlsruhe-Julich system for a 50-meter release height and rough surface, and
- "St. Louis" system for urban areas as taken from Vogt.

The Pasquill-Gifford dispersion parameters were determined in flat terrain with prairie grass vegetation with a short-term (3 minute) ground-level release. These are the values traditionally used in DOE and NRC accident consequence analyses. Compensation for various surface roughnesses and plume meander can be made by including a scale factor as described in the next section.

The Karlsruhe-Julich set of dispersion parameters were determined with elevated releases and rough (> 1 meter) surface roughness and a one-hour release. (For a discussion of the surface roughness parameter, see for example Turner (Ref. 3), p. 1-3.)

The "St. Louis" parameters were determined for urban areas and the power function representation was suggested by Vogt.

While none of these systems accurately represent the surface characteristics of LANL, the Tadmor and Gur representation of the Pasquill-Gifford (P-G) dispersion parameters is favored when appropriately modified. Modifications should be made with appropriate scale factors for σ_y and σ_z to reflect plume meander and more surface roughness than the 3-minute release and flat terrain of their derivation. The experimental conditions surrounding the Karlsruhe-Jurich and St. Louis measurements are more representative of urban environments and consistently result in lower dose estimates (greater dispersion) than the scaled P-G parameters by as much as several times.

The P-G system has the benefit of common usage within the DOE and NRC and therefore their use provides continuity and ease of comparison. This is the system included in Regulatory Guide 1.145, Regulatory Position 1, which is referenced by DOE-STD-3009-94, Appendix A.

IV.A.1.e. Scaling Factors for Dispersion, Surface Roughness

MACCS2 provides for the ability to linearly scale both the horizontal and vertical dispersion parameters, σ_y and σ_z . The MACCS model description (Ref. 4), suggests that surface roughness be taken into account by scaling σ_z . The scale factor for σ_z is determined by:

$$Scale\ Factor = \left(\frac{z_1}{z_0} \right)^{0.2} \quad (4)$$

where: z_1 = surface roughness length of region of interest, and
 z_0 = reference surface roughness length

Tables of surface roughness length can be found both in Turner (Ref.3), page 1-3 and in the NRC study (Ref. 2), page 2-19. Comparing the descriptions in these tables with the surface features typical of LANL, it was determined that the most appropriate surface roughness for general use at LANL is 40 cm.

Data from the meteorological towers around LANL have been adjusted (toward lower dispersion) by a factor of $(40/15)^{0.2} = 1.22$. In order to reconstruct the original data, one must put this factor back in, so the σ_z scale factor that should be used is 1.22. Other scale factors may be used if justified on the basis of local physical conditions.

IV.A.1.f. Plume Meander

A plume does not typically follow a straight-line trajectory in the real world. MACCS2 models this effect by applying a scaling factor to the horizontal dispersion parameter (σ_y) based on the duration of the release compared to the duration of the release in the field experiments that are the basis for the reference dispersion parameters.

$$\sigma_y = \sigma_{ref} \left[\frac{\Delta t}{\Delta t_{ref}} \right]^m \quad (5)$$

where: σ_y = the corrected horizontal dispersion parameter,
 σ_{ref} = the uncorrected horizontal dispersion parameter,
 Δt = release duration,
 Δt_{ref} = release duration of the experiments that support the P-G dispersion parameters (3 minutes), and
 $m = 0.2$ for releases less than 1 hour and 0.25 for releases greater than 1 hr.

There is some disagreement in the literature over the value of Δt_{ref} ; some sources use 3 minutes and others use 10 minutes. The NRC study (Ref. 2) uses 3 minutes, so this is the value LANL will use.

The value of Δt is to be determined by the dynamics of the postulated accidental release. In the absence of technically defensible specific value for Δt , 3 minutes should be used. This has the effect of turning off the plume meander effect since the fraction raised to the m^{th} power is 1 and $\sigma_y = \sigma_{ref}$.

An example of how a longer duration release could be justified can be demonstrated by considering a release to the interior of a building with six air changes per hour (typical industrial ventilation design) with 100% exhaust. Assuming perfect mixing, 90% of the contaminant will be exhausted in 23 minutes (exponential decay). In this case, an assumed release time of 23 minutes would be justified).

The MACCS2 parameters for Δt and Δt_{ref} are PLDUR and TIMBAS respectively. YSCALE is a different, independent user-defined scale factor that should always be set to 1.0.

IV.A.1.g. Release Height

The height of release of the plume (MACCS2 variable, PLHITE) is the actual physical release height without the effects of momentum rise or thermal buoyancy. These effects are included with their respective models as described below.

Releases from building vents and windows are treated with a building wake model, also described below.

Release heights from stacks will lower downwind dose estimates according to the factor:

$$e^{-\frac{H^2}{2\sigma_z^2}}. \quad (6)$$

It should be remembered, however, that if this reduction is necessary for the dose estimates to be less than the off-site evaluation guideline (25 rem), the stack itself would then be designated as a safety class structure.

An elevated release model should not be used to represent releases at the edge of a canyon. Section 4.17 of Turner (Ref. 3), page 4-17 states: "With downslope flow when the receptor is at a lower elevation than the source, a likely assumption is that the flow parallels the slope; i.e. no allowance is made for the difference between groundlevel elevations at the source and at the receptor."

IV.A.1.h. Sensible Heat

The amount of sensible heat in the released plume is entered into MACCS2 with the parameter "PLHEAT". This value is in units of watts (joules/sec) where the energy released must be divided by the duration of the plume (PLUDUR). This parameter is used to determine the amount of buoyant plume rise as described below.

The amount of sensible heat for a room temperature plume is 0. Of the energy released in an accident (e.g. fire) that does not involve the building structure, only 10% is assumed to be contained in the plume that escapes the building; the remainder is assumed to be absorbed by the building structure. A fire hazard analysis is necessary to provide a basis for the value of PLHEAT used.

IV.A.1.i. Buoyancy

With heat content, a plume will rise due to buoyancy. This model is used only for releases into a building wake, not from an elevated stack. If the analyst wishes to consider buoyancy after release from a stack, this must be done off-line according to the methods described by Turner (Ref. 3), Chapter 3 and the results incorporated into the MACCS2 parameter PLHITE. See also the discussion on momentum rise below.

The first thing MACCS2 does is determine a critical wind speed necessary for the plume to escape the building wake. If the heat content is sufficient to lift the plume above the building wake, it then applies a plume rise model described in detail in the Model Description document (Ref. 4). While the model parameters are fixed in the code, scale factors are available to the user to modify the end result. These are SCLADP and SCLEFP. At LANL they are set to 1.0.

IV.A.1.j. Momentum Rise

Most stack releases are driven by a ventilation system that provides vertical speed that results in a momentum rise above the physical stack height. This is not treated in MACCS2 but could be included in the consequence analysis at the discretion of the analyst. A model for momentum rise (depending on stability class) can be found in Turner (Ref. 3), Chapter 3.

This Turner method compares buoyant and momentum rise using the higher of the two in the determination of the final plume rise and, hence, the effective plume height. If momentum is significant in the accident scenario, it is suggested that this comparison be performed according to the Turner method and if the momentum rise is greater than the buoyancy rise, turn off the buoyancy rise (PLHEAT = 0.0) and add the momentum rise to the stack height to arrive at an effective height (PLHITE). Note that the Turner method distinguishes between stability classes. If this method is used, the appropriate value is the one determined for stable conditions.

Again, it should be remembered, that if the reduction in dose estimate provided by the increase in effective stack height is necessary for the estimates to be less than the off-site evaluation guideline (25 rem), the stack and ventilation system would then be designated as safety class structures, systems and components (SSCs).

IV.A.1.k. Wake Effects

Building wake is modeled by setting the initial values of the atmospheric dispersion parameters σ_y and σ_z . Of the options listed in the MACCS2 User's Guide, the ones to be used at LANL are:

$$\sigma_y(\text{initial}) = \frac{W}{4.3} = \text{SIGYINIT} \quad (7)$$

and

$$\sigma_z(\text{initial}) = \frac{H}{2.15} = \text{SIGZINIT} \quad (8)$$

where: W = building width
 H = building height.

Since the determination of the site 95% χ/Q dispersion includes all wind directions, the building width and height associated with the smallest cross sectional area should be used in the building wake model. This is consistent with the method described in Reg Guide 1.145 (Ref. 5), page 3.

It is important to recognize that MACCS2 handles building wake only for a plume released into the building wake and not from an elevated stack. Once σ_y (initial) and σ_z (initial) are defined, they are fixed. If, in addition, a PLHITE value is defined, it is modeled as a plume beginning at the elevation defined by PLHITE AND initial σ_y and σ_z as also defined.

Other codes are available that incorporate models for combinations of elevated release from a stack in combination with building wake. GENII, for example, uses a "split-H" model to partition the plume between the elevated release and building wake for release heights greater than the building height but less than 2-1/2 times the building height.

IV.A.1.I. Meteorological Sampling Specifications

There are five options in MACCS2 for handling the weather data. Direction-dependent calculations usually make use of the bin sampling provided by setting the parameter METCOD to the value 2. This option could still be used for analyses to estimate dose to on-site, non-facility workers. For comparison to off-site evaluation guidelines, however, the atmospheric dispersion at the site boundary must be estimated according to the direction provided by Appendix A of DOE-STD-3009-94. The only way to do this with MACCS2 is to set METCOD to the value 5 and NSMPLS = 24 (24 hourly samples per day). The output is then 8760 individual hourly values of χ/Q for the year selected. This data then must be manipulated to obtain a cumulative distribution function so the 95 percentile can be selected. (See Section IV.B below).

IV.A.2. Meteorological Input File from ESH-17

An input file of meteorological data is available from ESH-17 for complete years 1991 to the present from several meteorological towers suitable for use with MACCS2 from their web site at:

<http://weather.lanl.gov/cgi-bin/msfilerequest.pl>

Choose the tower located nearest the facility being analyzed. There is no guidance on which year's data to use; results generally do not vary by more than 10% from year-to-year.

IV.B. Post-Processing of MACCS2 Output

As noted above, the output from MACCS2 with METCOD set to five is 8760 individual hourly values for χ/Q . These data must be organized into a cumulative distribution function so that the 95% can be identified. This can be done with a post processor written by B. Letellier of D-11 (POSTMAX.EXE).

This program requires two files to run: the output file from MACCS2 with a file extension of ".out" and a file that defines the off-site boundary distances for each of the 16 compass directions with a file extension of ".bnd". The output filename is defined by the user and automatically is assigned the file extension ".cdf".

As noted above, the distance to the off-site boundary must be defined according to regulatory position 1.2 of Regulatory Guide 1.145. The pertinent part of regulatory position 1.2 is:

"For each of the 16 sectors (*N, NNE, NE,...*), the distance for exclusion area boundary or outer LPZ boundary χ/Q calculation should be the minimum distance from the stack or, in the case of releases through vents or building penetrations, the nearest point on the building to the exclusion area boundary or outer LPZ boundary within a 45-degree sector centered on the compass direction of interest.

"For stack releases, the maximum ground-level concentration in a sector may occur beyond the exclusion area boundary distance or outer LPZ boundary distance. Therefore, for stack releases, χ/Q calculations should be made in each sector at each minimum boundary distance and at various distances beyond the exclusion area boundary distance to determine the maximum relative concentration for consideration in subsequent calculations."

The distances to the site boundary in the 16 sectors must be determined according to these instructions without consideration of elevated (stack) releases described in the previous paragraph. These distances are provided to the POSTMAX.EXE and this program then queries the MACCS2 output file for the position of the maximum value of χ/Q . When the cumulative distribution function (cdf) of the χ/Q 's is formulated, it uses either the site-boundary χ/Q if the location of the maximum occurs within the site boundary, and the maximum χ/Q if it occurs beyond the site boundary. Thus POSTMAX.EXE automatically takes care of the situation where the maximum may occur beyond the site boundary because of an elevated release.

IV.C. Ground Shine and Direct Shine

Usually ground shine and direct (cloud) shine will not make significant contributions to the total off-site dose. They should not be categorically dismissed however, because in some cases they could be significant contributors.

At the Savannah River Site, analyses including the release of fission products do indicate significant ground shine doses. Nobel gases, e.g. ^{85}Kr , exhibit very little if any absorption in the lung, so the inhalation dose is very small and total dose is dominated by the β/γ radiation from the cloud. DOE-STD-3009-94, Appendix A requires consideration of a 2-

hour exposure to the plume. For inhalation and cloud shine, this will generally include the passage of the entire plume. For ground shine, it is defined as two hours.

MACCS2 does calculate dose due to ground shine and cloud shine with its EARLY subroutine. It does not do it, however, in a manner consistent with regulatory position 3 of Regulatory Guide 1.145. The analyst can, however, run the EARLY routine and compare inhalation dose to shine dose at a given distance or direction. If the shine dose is significant, it can be made consistent with the Regulatory Guide by applying the same proportion to the inhalation dose calculated with the regulatory position 3 method.

IV.D. Quasi-Instantaneous (Puff) Releases

DOE-STD-3009-94, Appendix A allows for the use of phenomenon-specific codes for "...accidents with unique dispersion characteristics, such as explosions..." For energetic releases, codes exist (e.g. ERAD) to model the release height and initial size. ERAD also models the down-wind dispersion of this short-term release using a monte carlo technique.

When using MACCS2, a quasi-instantaneous or puff release is a release of less duration than 3 minutes (the basis for the Pasquill-Gifford dispersion parameters). If the release is entrained within a continuous plume such as from a continuously functioning exhaust system, then it should be modeled as a continuous plume. If not, then it should be modeled as a puff release.

If one assumes the receptor at the site-boundary is in the center of the puff for the entire duration of the passage of the puff, the equation for the dispersion (χ/Q) is the same as for the plume (see Appendix B) but the horizontal and vertical dispersion parameters (σ_y and σ_z) have been determined experimentally to be significantly smaller than those for the plume model. This yields significantly higher dose estimates for an isolated puff than for a plume at the same distance and stability class. These puff dispersion parameters can be represented by power-law functions of down-wind distance and can be found in Turner (Ref. 3, page 4-21, Table 4.8).

V. References

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APPENDIX A

The following tables show the distances to site boundaries and outputs from MACCS2 and POSTMAX for each of the LANL nuclear facilities. The tables of dispersion values (χ/Q) are 95% values determined according to Appendix A of DOE-STD-3009-94. These were derived with no special compensation for wet or dry deposition, wake or plume meander, heat, buoyancy, or momentum rise. Various release heights are included. The dispersion values for plume releases have included a σ_z scale factor of 1.22. The dispersion values for the puff releases do not include a σ_z scale factor because the conditions of the experimentally derived dispersion parameters are not known. This may result in somewhat conservative results. In all cases, weather data was used from the meteorological tower nearest the nuclear facility for the calendar year 2001.

Table values can be used by the analyst in hazard analyses or for deciding which accident scenarios are candidates for more detailed analyses. The values provided here are conservative estimates of real scenarios.

TA-3-29
(CMR)

Distances to Site Boundary

Direction	Distance (m)
N	1097
NNE	1161
NE	1290
ENE	1484
E	1484
ESE	4386
SE	4386
SSE	4773
S	4386
SSW	4386
SW	3161
WSW	2516
W	2129
WNW	1548
NW	1226
NNW	1097

Atmospheric Dispersion (95% χ/Q) for Plume and Puff Releases at Various Effective Release Heights

Release Height (m)	Plume (χ/Q) (sec/m ³)	Puff (χ/Q) (sec/m ³)
0	1.7x10 ⁻⁴	8.8x10 ⁻⁴
10	1.6x10 ⁻⁴	5.4x10 ⁻⁴
20	1.2x10 ⁻⁴	2.3x10 ⁻⁴
30	7.8x10 ⁻⁵	1.2x10 ⁻⁴
40	5.5x10 ⁻⁵	6.9x10 ⁻⁵
50	3.9x10 ⁻⁵	4.7x10 ⁻⁵

TA-8-23

Distances to Site Boundary

Direction	Distance (m)
N	950
NNE	1484
NE	2322
ENE	3741
E	4257
ESE	6579
SE	3354
SSE	2774
S	2774
SSW	541
SW	434
WSW	434
W	434
WNW	438
NW	520
NNW	704

Atmospheric Dispersion (95% χ/Q) for Plume and Puff Releases at Various Effective Release Heights

Release Height (m)	Plume (χ/Q) (sec/m ³)	Puff (χ/Q) (sec/m ³)
0	2.8×10^{-4}	1.2×10^{-3}
10	2.5×10^{-4}	7.9×10^{-4}
20	1.8×10^{-4}	3.0×10^{-4}
30	1.2×10^{-4}	1.5×10^{-4}
40	7.3×10^{-5}	9.9×10^{-5}
50	5.1×10^{-5}	6.7×10^{-5}

(TA-16-205)
(WETF)

Distances to Site Boundary

Direction	Distance (m)
N	774
NNE	1355
NE	4902
ENE	5676
E	7160
ESE	1032
SE	710
SSE	645
S	645
SSW	645
SW	581
WSW	452
W	452
WNW	452
NW	452
NNW	645

Atmospheric Dispersion (95% χ/Q) for Plume and Puff Releases at Various Effective Release Heights

Release Height (m)	Plume (χ/Q) (sec/m ³)	Puff (χ/Q) (sec/m ³)
0	5.5×10^{-4}	3.0×10^{-3}
10	4.6×10^{-4}	1.1×10^{-3}
20	2.6×10^{-4}	3.6×10^{-4}
30	1.5×10^{-4}	1.7×10^{-4}
40	8.7×10^{-5}	1.0×10^{-4}
50	5.9×10^{-5}	6.8×10^{-5}

TA-18

Distances to Site Boundary

Direction	Distance (m)
N	896
NNE	968
NE	968
ENE	968
E	1226
ESE	1548
SE	4322
SSE	5805
S	4515
SSW	4515
SW	4386
WSW	4386
W	4644
WNW	6579
NW	1613
NNW	1290

Atmospheric Dispersion (95% χ/Q) for Plume and Puff Releases at Various Effective Release Heights

Release Height (m)	Plume (χ/Q) (sec/m ³)	Puff (χ/Q) (sec/m ³)
0	2.3×10^{-4}	1.3×10^{-3}
10	1.9×10^{-4}	5.4×10^{-4}
20	1.2×10^{-4}	1.8×10^{-4}
30	6.9×10^{-5}	8.6×10^{-5}
40	4.5×10^{-5}	5.2×10^{-5}
50	3.0×10^{-5}	3.5×10^{-5}

TA-21-155 & -209

Distances to Site Boundary

Direction	Distance (m)
N	392
NNE	392
NE	392
ENE	469
E	676
ESE	1068
SE	2322
SSE	2129
S	2129
SSW	2129
SW	6902
WSW	6837
W	1363
WNW	687
NW	458
NNW	392

Atmospheric Dispersion (95% χ/Q) for Plume and Puff Releases at Various Effective Release Heights

Release Height (m)	Plume (χ/Q) (sec/m ³)	Puff (χ/Q) (sec/m ³)
0	6.5×10^{-4}	3.5×10^{-3}
10	5.3×10^{-4}	1.1×10^{-3}
20	2.7×10^{-4}	2.9×10^{-4}
30	1.4×10^{-4}	1.4×10^{-4}
40	7.5×10^{-5}	8.0×10^{-5}
50	4.8×10^{-5}	5.6×10^{-5}

TA-48-1

Distances to Site Boundary

Direction	Distance (m)
N	710
NNE	710
NE	806
ENE	1935
E	2967
ESE	2903
SE	2903
SSE	5418
S	4451
SSW	4451
SW	4451
WSW	4193
W	3612
WNW	2322
NW	1935
NNW	1419

Atmospheric Dispersion (95% χ/Q) for Plume and Puff Releases at Various Effective Release Heights

Release Height (m)	Plume (χ/Q) (sec/m ³)	Puff (χ/Q) (sec/m ³)
0	1.6×10^{-4}	8.4×10^{-4}
10	1.6×10^{-4}	5.6×10^{-4}
20	1.3×10^{-4}	2.2×10^{-4}
30	8.3×10^{-5}	1.1×10^{-4}
40	5.3×10^{-5}	6.6×10^{-5}
50	3.5×10^{-5}	4.5×10^{-5}

TA-50-1,-2,-37,-66,-69, & -90

Distances to Site Boundary

Direction	Distance (m)
N	1193
NNE	1806
NE	2258
ENE	2838
E	2064
ESE	2064
SE	3419
SSE	5676
S	4451
SSW	4257
SW	4257
WSW	4709
W	4451
WNW	3032
NW	1355
NNW	1193

Atmospheric Dispersion (95% χ/Q) for Plume and Puff Releases at Various Effective Release Heights

Release Height (m)	Plume (χ/Q) (sec/m ³)	Puff (χ/Q) (sec/m ³)
0	1.0×10^{-4}	5.6×10^{-4}
10	9.8×10^{-5}	4.0×10^{-4}
20	8.3×10^{-5}	1.8×10^{-4}
30	6.1×10^{-5}	1.0×10^{-4}
40	4.3×10^{-5}	6.3×10^{-5}
50	3.0×10^{-5}	4.2×10^{-5}

TA-53-7
(1L Target & ER-1/2)

Distances to Site Boundary

Direction	Distance (m)
N	903
NNE	903
NE	1032
ENE	1161
E	1613
ESE	1806
SE	1355
SSE	1290
S	1290
SSW	1290
SW	1419
WSW	1806
W	3225
WNW	1935
NW	1290
NNW	903

Atmospheric Dispersion (95% χ/Q) for Plume and Puff Releases at Various Effective Release Heights

Release Height (m)	Plume (χ/Q) (sec/m ³)	Puff (χ/Q) (sec/m ³)
0	2.6×10^{-4}	1.5×10^{-3}
10	2.4×10^{-4}	8.1×10^{-4}
20	1.8×10^{-4}	3.1×10^{-4}
30	1.2×10^{-4}	1.5×10^{-4}
40	7.5×10^{-5}	7.8×10^{-5}
50	5.3×10^{-5}	4.8×10^{-5}

TA-54-33

Distances to Site Boundary

Direction	Distance (m)
N	246
NNE	246
NE	246
ENE	273
E	382
ESE	956
SE	1935
SSE	2258
S	5999
SSW	5095
SW	5095
WSW	5095
W	5934
WNW	2184
NW	273
NNW	246

Atmospheric Dispersion (95% χ/Q) for Plume and Puff Releases at Various Effective Release Heights

Release Height (m)	Plume (χ/Q) (sec/m ³)	Puff (χ/Q) (sec/m ³)
0	1.5×10^{-3}	8.8×10^{-3}
10	6.9×10^{-4}	9.3×10^{-4}
20	2.5×10^{-4}	2.6×10^{-4}
30	1.1×10^{-4}	1.4×10^{-4}
40	6.6×10^{-5}	8.9×10^{-5}
50	4.4×10^{-5}	6.3×10^{-5}

TA-54-38
(RANT)

Distances to Site Boundary

Direction	Distance (m)
N	499
NNE	416
NE	416
ENE	416
E	554
ESE	970
SE	1856
SSE	5160
S	5096
SSW	4838
SW	4838
WSW	4838
W	5225
WNW	4257
NW	839
NNW	776

Atmospheric Dispersion (95% χ/Q) for Plume and Puff Releases at Various Effective Release Heights

Release Height (m)	Plume (χ/Q) (sec/m ³)	Puff (χ/Q) (sec/m ³)
0	7.5×10^{-4}	4.4×10^{-3}
10	4.8×10^{-4}	8.1×10^{-4}
20	2.0×10^{-4}	2.2×10^{-4}
30	9.9×10^{-5}	1.1×10^{-4}
40	5.8×10^{-5}	6.3×10^{-5}
50	3.7×10^{-5}	4.2×10^{-5}

TA-54-Pad 2

Distances to Site Boundary

Direction	Distance (m)
N	273
NNE	273
NE	273
ENE	328
E	478
ESE	710
SE	1355
SSE	1355
S	2193
SSW	5354
SW	5354
WSW	5354
W	6257
WNW	519
NW	328
NNW	273

Atmospheric Dispersion (95% χ/Q) for Plume and Puff Releases at Various Effective Release Heights

Release Height (m)	Plume (χ/Q) (sec/m ³)	Puff (χ/Q) (sec/m ³)
0	1.2×10^{-3}	6.8×10^{-3}
10	6.4×10^{-4}	9.8×10^{-4}
20	2.5×10^{-4}	2.7×10^{-4}
30	1.2×10^{-4}	1.4×10^{-4}
40	7.0×10^{-5}	8.6×10^{-5}
50	4.8×10^{-5}	6.3×10^{-5}

TA-55-4

Distances to Site Boundary

Direction	Distance (m)
N	968
NNE	968
NE	1613
ENE	2709
E	2451
ESE	2451
SE	2451
SSE	5676
S	4322
SSW	4322
SW	4322
WSW	4709
W	4128
WNW	2677
NW	2193
NNW	968

Atmospheric Dispersion (95% χ/Q) for Plume and Puff Releases at Various Effective Release Heights

Release Height (m)	Plume χ/Q (sec/m ³)	Puff χ/Q (sec/m ³)
0	1.2×10^{-4}	6.2×10^{-4}
10	1.1×10^{-4}	4.4×10^{-4}
20	9.3×10^{-5}	2.0×10^{-4}
30	6.9×10^{-5}	1.1×10^{-4}
40	4.8×10^{-5}	6.4×10^{-5}
50	3.3×10^{-5}	4.4×10^{-5}

APPENDIX B

Time Integral of a Puff Release

In Section IV.D, it is stated that if it is assumed that if one assumes the receptor at the site-boundary is in the center of the puff for the entire duration of the passage of the puff, the equation for the dispersion (χ/Q) is the same as for the plume. In order to demonstrate this, one must take the receptor to be at a fixed location, X , and integrate the expression for a puff release over time from $t = -\infty$ to $+\infty$.

According to Turner (Ref. 3) page 4-19, the equation for a ground-level puff release (elevation of release does not affect these results) and a ground-level receptor in the center of the puff is:

$$\chi = \frac{2Q_T}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \exp\left[-\frac{(x-ut)^2}{2\sigma_x^2}\right] \quad (B-1)$$

where: Q_T = the total time-integrated release of the radionuclide

The dispersion parameters σ_x , σ_y , and σ_z are expressed only as functions of x , however an exact solution to the time integral would convert to functions of t by assuming $x = ut$, where u is the wind velocity. This would account for the fact that the puff expands as it passes the receptor. This, however, leads to a rather intractable integral.

By examining the σ 's as a function of x it can be shown that they are nearly linear in the range of interest to us. Below are linear graphs of σ_x and σ_z as a function of x (the puff model assumes $\sigma_y = \sigma_x$).

Provided we can assume a linear relationship of the dispersion parameters with distance (and, therefore, time), it is a fair approximation just to use the single value of sigma for the position of the receptor since the higher concentration, shorter duration of the plume at the beginning of exposure will be exactly compensated for by the lower concentration, longer duration at the end of the exposure. So, the time integral is performed assuming the dispersion parameters are a constant with time and equal to their value at the position of the receptor.

$$\int_{-\infty}^{\infty} \chi / Q_T dt = \frac{2}{(2\pi)^{3/2} \sigma_x(X) \sigma_y(X) \sigma_z(X)} \int_{-\infty}^{\infty} \exp \left[\frac{-(X - ut)^2}{2\sigma_x(X)^2} \right] dt \quad (B-2)$$

The integral on the right can be evaluated by changing variables so that:

$$Z = X - ut,$$

$$dZ/dt = -u$$

$$dt = -dZ/u$$

and changing the limits of integration to reflect that when:

$$t = -\infty, Z = +\infty \text{ and when:}$$

$$t = +\infty, Z = -\infty.$$

So the integral becomes:

$$-\frac{1}{u} \int_{+\infty}^{-\infty} \exp \left[\frac{-Z^2}{2\sigma_x(X)^2} \right] dZ \quad (B-3)$$

The solution of this integral is:

$$\frac{\sqrt{2\pi}\sigma_x(X)}{2} \operatorname{erf} \left[\frac{\sqrt{2}z}{2\sigma_x(X)} \right]_{-\infty}^{+\infty} \quad (\text{B-4})$$

Since $\operatorname{erf}(-\infty) = -1$ and $\operatorname{erf}(+\infty) = +1$, this integral is:

$$\frac{\sqrt{2\pi}\sigma_x(X)}{2} (-2) = -\sqrt{2\pi}\sigma_x(X) \quad (\text{B-5})$$

and:

(A-3) becomes:

$$\frac{\sqrt{2\pi}\sigma_x(X)}{u} \quad (\text{B-6})$$

Finally,

$$\int_{-\infty}^{+\infty} \chi / Q_T \, dt = \frac{2}{(2\pi)^{3/2} \sigma_x(X) \sigma_y(X) \sigma_z(X)} \left[\frac{\sqrt{2\pi}\sigma_x(X)}{u} \right] \quad (\text{B-7})$$

and,

$$\int_{-\infty}^{+\infty} \chi / Q_T \, dt = \frac{2}{(2\pi)u\sigma_y(X)\sigma_z(X)} = \frac{1}{\pi u\sigma_y(X)\sigma_z(X)} \quad (\text{B-8})$$

Which is the exact expression for the plume found in Turner, page 2-6, equation (2.5) if one integrates Turner's equation from $t = 0$ to $t = \infty$ to convert his Q to Q_T .

APPENDIX C

Determination of the Location of Maximum χ/Q

In order for the postprocessor, POSTMAX.EXE, to work, the position of the maximum χ/Q must not fall beyond the mid-point of the last spatial interval defined in MACCS2. It is useful therefore, to know where the position of the maximum χ/Q is for elevated releases. This maximum depends on the stability class, but the F stability class is always the worst case.

The location of the maximum χ/Q can be determined analytically by differentiating the expression for χ/Q , setting it equal to zero and solving for x as follows:

For an elevated release and the receptor at ground-level and in the centerline of the plume (puff):

$$\chi/Q = \frac{1}{\pi u \sigma_y(x) \sigma_z(x)} \exp\left[\frac{-H^2}{2\sigma_z(x)^2}\right] \quad (C-1)$$

The diffusion parameters $\sigma_y(x)$ and $\sigma_z(x)$ are represented as power functions provided by Tadmor and Gur (Ref. 1) as:

$$\sigma_y = ax^b \text{ and } \sigma_z = cx^d \quad (C-2)$$

Substituting into (C-1),

$$\chi/Q = \frac{1}{\pi u (ax^b)(cx^d)} \exp\left[\frac{-H^2}{2(cx^d)^2}\right] \text{ or} \quad (C-3)$$

$$\chi/Q = \frac{1}{\pi u a c x^{b+d}} \exp\left[\frac{-H^2}{2c^2 x^{2d}}\right] \quad (C-4)$$

This can be differentiated by part:

$$\frac{d}{dx}(\chi/Q) = \frac{d}{dx}\left(\frac{x^{-(b+d)}}{\pi u a c}\right) \exp\left[\frac{-H^2}{2c^2 x^{2d}}\right] + \frac{x^{-(b+d)}}{\pi u a c} \frac{d}{dx} \left\{ \exp\left[\frac{-H^2}{2c^2 x^{2d}}\right] \right\} \quad (C-5)$$

$$\frac{d}{dx}(\chi/Q) = \frac{-(b+d)x^{-(b+d+1)}}{\pi u a c} \exp\left[\frac{-H^2}{2c^2 x^{2d}}\right] + \frac{x^{-(b+d)}}{\pi u a c} \left[\frac{H^2 dx^{-(2d+1)}}{c^2} \right] \exp\left[\frac{-H^2}{2c^2 x^{2d}}\right] \quad (C-6)$$

$$\frac{d}{dx}(\chi/Q) = \left\{ \frac{-(b+d)x^{-(b+d+1)}}{\pi u a c} + \frac{x^{-(b+d)} H^2 dx^{-(2d+1)}}{\pi u a c^3} \right\} \exp\left[\frac{-H^2}{2c^2 x^{2d}}\right] \quad (C-7)$$

Setting this to = 0, results in the following:

$$\frac{(b+d)x^{-(b+d+1)}}{\pi u a c} = \frac{x^{-(b+3d+1)} H^2 d}{\pi u a c^3} \quad (\text{C-8})$$

$$x^{2d}(b+d) = \frac{H^2 d}{c^2} \quad (\text{C-9})$$

$$x^{2d} = \frac{H^2 d}{c^2(b+d)} \quad (\text{C-10})$$

$$x_{\max} = \left[\frac{H^2 d}{c^2(b+d)} \right]^{1/2d} \quad (\text{C-11})$$